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The acoustic bubble: Oceanic bubble acoustics and ultrasonic cleaning

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Bubbles interact strongly with sound fields. Gas bubbles in the ocean generate sound as they are produced by breaking waves, rainfall, methane seeps, etc., and such emissions can be used to size and count the bubbles present. However after production, when the pulsations of such bubbles have damped away, they are silent unless re-excited. These, and other bubbles in the ocean that do not generally make significant passive sound emissions (such as those that appear through exsolution, and a range of biological processes including decomposition, photosynthesis, respiration and digestion) can still strongly influence applied sound fields through scattering, and changing the sound speed and absorption from that which would be expected in bubble-free water. This paper discusses how these phenomena might be associated with bubble netting by cetaceans. When driven with appropriate acoustic fields, bubbles can change their surrounding environment, and examples of this are shown through the generation of cleaning in an ultrasonically-activated stream of cold water, without additives.

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I. INTRODUCTION

Gas bubbles in liquids interact strongly with sound fields, generating and scattering them, and causing significant changes to the sound speed and absorption at some frequencies (depending on the bubble size) [1]. Examples of this from ocean acoustics will be given (section II). Applied sound fields can cause bubble wall motions that can change the local environment, and examples of how this is done in a new ultrasonic cleaning technology are shown (section III).

II. OCEANIC BUBBLE ACOUSTICS

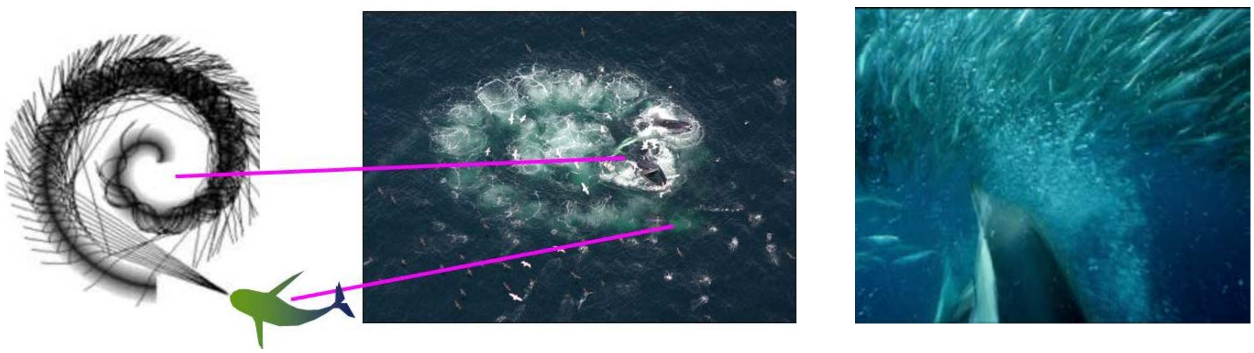
Figure 1(a) shows an image of the aftermath of a water drop impacting a body of water, the half-submerged lens clearly revealing the water jet that rises into the air as, below it, the crater shrinks in the water surface [2]. However, the famous ‘plink’ sound of a dripping tap is not caused by either of these features: it is generated by the tiny bubble that was pinched off from the base of the closing crater [3, 4]. This illustrates how powerful an acoustical entity is a gas bubble in liquid. Each bubble behaves like an underwater bell, small ones producing ‘plinks’ of high notes, and larger ones generating low notes [5]. From such early studies has now grown substantial coverage of acoustic rainfall monitoring over the oceans [6, 7].

When an ocean wave breaks, therefore, it generates many bubbles, each ‘singing’ its own note, and from the overall sound we can determine the number and size of bubbles containing trapped atmospheric gas, which can form bubble clouds in the upper ocean [Figure 1(b)] [8]. These bubbles are responsible for the transfer between atmosphere and ocean of many hundreds of millions of tonnes of atmospheric carbon each year [9, 10]. However, to quantify this climatically-important carbon transfer, it is not sufficient simply to know how many bubbles are injected into the ocean by breaking waves. One must also know how many are left some time after the wave has broken, after some bubbles have risen to the surface, and others have dissolved. To do this, we project sound at the bubble clouds [11-14], and from the scatter we quantify how this undersea bubble population evolves, producing models of the shape and size of the undersea bubble clouds [Figure 1(c)]. Such models [15-17] allow us to quantify the effect of bubbles on the transfer of carbon between atmosphere and ocean.

(a) *(b)* *(c)*

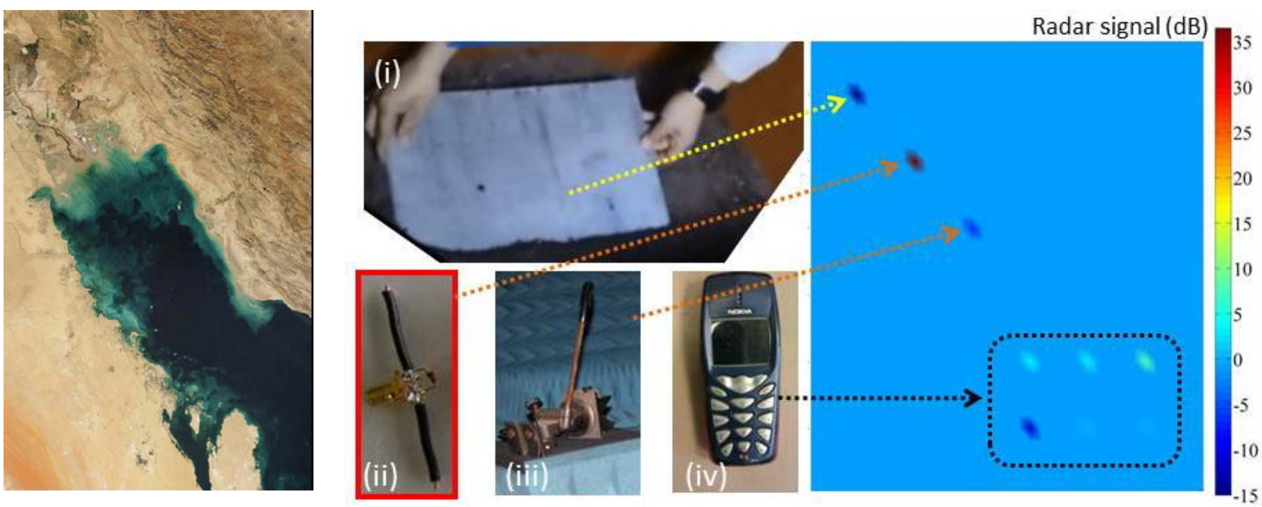
Fig 1. (a) The aftermath of a water drop impact on a body of water. (b) Undersea bubble clouds. (c) Frame shot of bubble clouds modelled after waves have broken in a region of ocean.

Our ability to model the scattering of sound by undersea bubbles allowed us to postulate the mechanism by which humpback whales trap prey within spiral bubble nets. Although it had been known for decades that whales blow bubbles to do this, the reason why the prey do not escape the trap was not known [5]. Our models [Figure 2(a)] showed that the spiral bubble net traps the loud calls emitted by whales to produce an impassable ‘wall of sound’, whilst simultaneously creating a quiet zone in which the prey would congregate, this zone occurring in the model at the exact location where the rising whales feed [as photographed in Figure 2(a)] [18].



(a) *(b)*

Figure 2. (a) Model (left) of acoustic rays based on a photographed spiral bubble net (photo by T. Voorheis of Gulf of Maine Production). (b) Image of a dolphin blowing bubbles to catch fish (Image courtesy of The Blue Planet. BBC).



(a) *(b)*

Figure 3. (a) Aerial image of Persian Gulf (mage courtesy J. Descloitres, MODIS Land Rapid Response Team at NASA GSFC). (b) TWIPR Radar signal from (i) an aluminium plate, (ii) a circuit resembling components of a bomb trigger; (iii) a rusty bench clamp; (iv) mobile phones in various states (on, off, or with invalid SIM cards) See [24] for details.

However, unlike humpback whales, dolphins use high frequency sonar to find prey, and the bubble nets they create [Figure 2(b)] would confound their sonar. Rather than accept that such dolphins would ‘blind’ their most spectacular sensory apparatus when hunting, we set about proving that a previously unknown type of sonar processing (TWIPS) could detect prey in bubble nets [19, 20], and showed this to work with dolphin sonar calls [21]. Although the question of whether odontocetes use such a method or not is still open to question [22, 23]. Industry is now developing this to protect shipping in coastal regions such as the Persian Gulf, where clouds of bubbles and particles in the near-shore waters make mine detection difficult [Figure 3(a)]. Realizing that this new processing system could work with radiations other than just sonar, we used it to develop a radar system (TWIPR) where the scattering off circuitry from a bomb trigger was in excess of 30 dB more powerful than the scattering off other targets [Figure 3(b)] [24]. With the ability selectively to detect mobile phones as readily as bomb triggers, TWIPR can help finding buried targets of interest (bombs, people carrying phones buried by collapsed buildings or avalanches) where normal radar would not be able to identify the genuine target from other debris [typified in Fig 3(b) by (i) & (iii)].

III. COLD WATER CLEANING IN AN ULTRASONICALLY ACTIVATED STREAM

(a) Without additives

The strong interaction between bubbles and sound has enabled a range of applications for medical diagnosis and therapy, in industrial processing and monitoring (e.g. for processing foodstuffs, pharmaceuticals and domestic products). One particular innovation was the Ultrasonically Activated Stream (UAS, invented at the University of Southampton and now in production by Ultrawave Ltd. under the name StarStream®), which enhances the cleaning ability of liquids, and in particular enables cold water cleaning.

Choice of device for cleaning depends on the scenario and resources one wishes to use. Pressure washers are effective, and can always be scaled up to produce enormous pressure. However the high resource usage (power, water and additives) are drawbacks for some scenarios using pressure washers. Other drawbacks include the production of backsplash, aerosol and spray, which can carry and redistribute contaminants onto the user (and which can be inhaled, settle on skin or eyes etc.) and nearby articles. The importance of such redistribution depends on the application, and would differ depending on whether the contaminant contained sewage, bacteria, radionucleotides, petrochemicals or the chemical ingratiates of marine antifoul.

Another drawback of pressure washers is the large volumes of liquid they use (up to 20 liters per minute for a large domestic pressure washer), and consequently lead to large volumes of contaminated run-off. This is linked to the expense, and problems in the run-off, of the use of soaps, salts and additives with pressure washers.

Pressure washers are also difficult to scale up (in terms of using multiple nozzles or larger nozzles), both because of the pump requirements (in terms of power and water usage), and because they generate considerable back force when used, meaning that the structural support for scaled up versions must become increasingly robust.

Ultrasonics, of course, has an established record in cleaning, in the form of the ultrasonic cleaning bath [25]. However the object to be cleaned must be small enough to fit within the bath. Moreover, the object to be cleaned in a bath sits in a contaminated ‘soup’ that can re-contaminate areas and persists as a film on the object after it is removed from the bath. Furthermore placement of items within the bath can ‘quench’ its cleaning ability by disturbing the ultrasonic field [26]. The UAS in some ways brings the power of an ultrasonic cleaning bath to the end of a hose, so that items can be ‘cleaned in place’. Both the UAS and the ultrasonic cleaning bath replace the pressure and flow that comes purely from the stream of water in the pressure washer, with pressure and flow close to a bubble wall. However, it would not be correct to equate the bubble activity in the cleaning bath with that which occurs in the UAS. The ultrasonic cleaning bath causes cavitation, whereby bubbles collapse under ultrasound to generate shock waves [27-29] and can also involute to form microjets [30,31], both of which can remove material from surfaces [32, 33]. In contrast, the UAS system projects sound down a column of water [34] in order to excite surface waves [35-37] on the walls of microscopic bubbles on the surface to be cleaned. These surface waves can generate convection [38-40] and shear forces [1, 41, 42] in the liquid close to the bubble wall, and so produce a cleaning effect, and alter the way material deposits onto surfaces [43].

The design, construction and operation of the UAS device are detailed elsewhere [44, 45], but the basic principle is that cold water is fed into a hollow horn that contains an ultrasonic transducer operating in excess of 100 kHz. The ultrasound and microbubbles in the flow both travel down the stream of water to the target that is to be cleaned. If the bubbles are ultrasonically activated when they are on the target, the cleaning ability of the liquid is enhanced in four ways (figure 4):

- The bubbles are attracted to the surface to be cleaned by Bjerknes radiation forces [1], and are not as rapidly washed away by the flow as they would be in the absence of ultrasound.
- The bubbles are particularly attracted into crevices by secondary Bjerknes radiation forces [1]; such crevices are traditionally more difficult to clean by wiping or brushing.
- Surface waves on the walls of the bubble, excited by the ultrasound, produce enhanced convection in the liquid and enhanced shear in the contaminant, causing its removal.
- The progress of the bubble into the crevices would, if the liquid contained additives (e.g. detergent or biocide) cause that additive to penetrate the crevice far more rapidly than would reliance on simple diffusion, so that cleaning can potentially be achieved more rapidly, and with lower concentrations of additives.

This UAS method has already demonstrated its efficacy in removing dental bacterial biofilms, and cleaning bone, skin models, and removing brain tissue from surgical steel [46-48]. Here a range of other applications are shown. In all of them, the UAS system was a commercial StarStream device that projected, into the liquid stream, only cold water directly from the mains water supply, without additives or heating, at a flow rate of around 1 litre per minute.

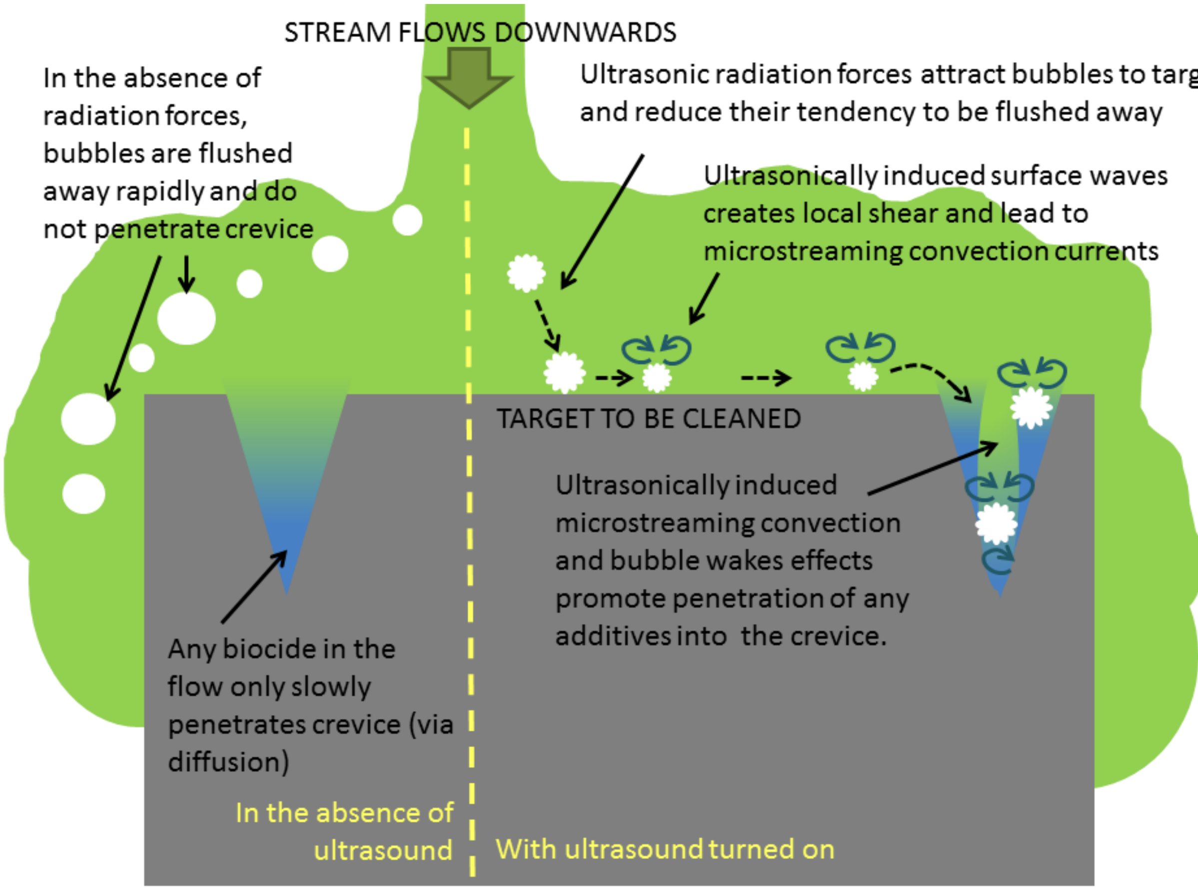


Figure 4. Schematic showing the four ways in which the UAS enhances cleaning (on the right) compared to the case when ultrasound is not present (on the left). Liquid shown in green issues from the nozzle, and may or may not have additives in it. Material shown in blue pre-existed in the crevices prior to the release of liquid from the nozzle, and is deficient of the additives (e.g. detergents or biocides) used to help decontamination.

Figure 5. The StarStream device is shown removing contaminant from the author's hand (the timings in the slide are approximate) using cold water without additives. The video of this will be made available via *http://www.southampton.ac.uk/engineering/research/projects/starstream.page?* .

In figure 5, the contaminant is fluorescent particulate tracer (Wash & Glow UV Germ Training Lotion), made visible using an 'blacklight' torch that contains significant ultraviolet energy. At first the UAS device is turned off and only cold water is projected onto the hand. After about 1 s the UAS is turned on, causing ultrasound and microbubbles to travel down the stream of water. Once activated, the device quickly removes the contaminant.

Figure 6 shows the UAS device removing a rusty deposit on a stainless steel sink, caused by placement on it, overnight, of a clamp stand (the sink itself did not rust). The rust was not removed by the cold water stream alone, until the ultrasound and bubbles in the UAS were activated.

Figure 7 shows the UAS removing aluminum oxide powder that has been ground into the grooves in a workshop file, and figure 8 shows removal of the glue used by the retailer to attach a label to a jam jar, neither of which could be removed by the cold water stream without the addition of ultrasound.

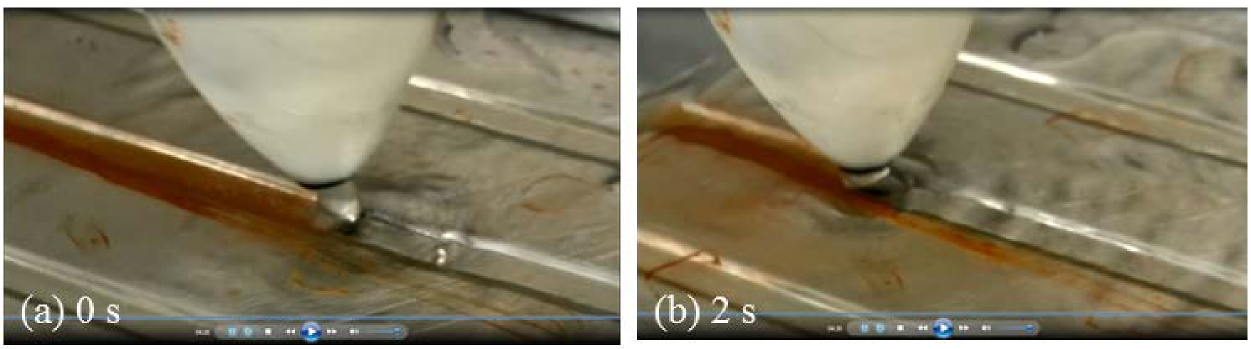


Figure 6. Removal by the UAS of a deposit of rust left on stainless steel by run-off from a clamp stand placed on the draining board overnight. The video from which this is selected (at the end of the video) will be made available via http://www.southampton.ac.uk/engineering/research/projects/starstream.page? .

Figure 7. Removal by the UAS of aluminum oxide powder from the grooves in a workshop file. The video of this will be made available via http://www.southampton.ac.uk/engineering/research/projects/starstream.page? .

As the final example of detergent-free cold water cleaning, figure 9 shows four frames from a split-screen video, where the UAS device is held above a 30 cm long glass tube, the base of which has been marked by mascara make-up that has been allowed to dry. The right side of each panel shows the overall view, whilst the left side shows a close-up of the base of the tube. Eight seconds [from panel (a) to panel (b)] of cold water ultrasound removes some of the mascara. The ultrasound is switched on just after panel (b) and within 2 s has removed [by panel (c)] significantly more.

Figure 8. Removal by the UAS of glue used to attach label to jam jar. The video of this is available at: https://www.youtube.com/watch?v=0H3ZE9IrgoQ .

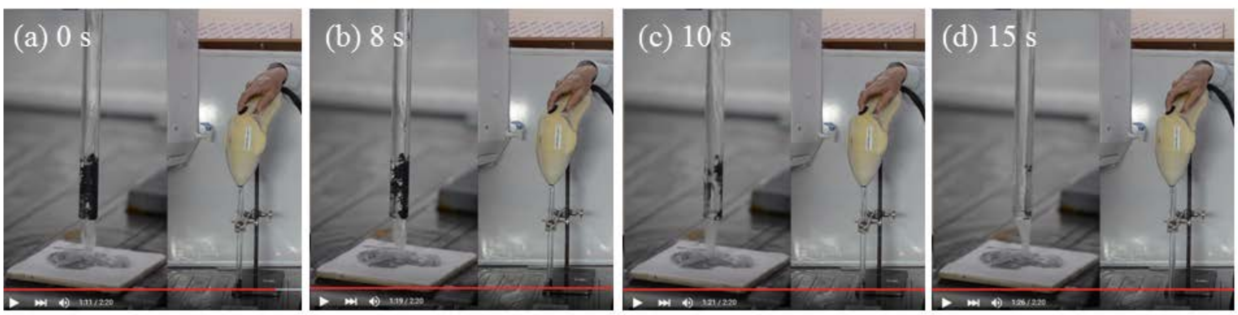


Figure 9. The base of a 30 cm long hollow glass tube is contaminated with dried-on mascara. Four panels from the split-screen video are shown, at (a) 0 s (just after cold water without ultrasound began to be projected down to the tube), (b) 8 s (just as the ultrasound was turned on), (c) 10 s and (d) 15 s. The video of this is available at: https://www.youtube.com/watch?v=g2qWOuNLB2A .

(b) When detergent is required

In some circumstances, cold water on its own is not sufficient to clean. Two examples of this are here taken from the rail industry.

Figure 10 shows stills, taken from a video, of a Perpetuum condition monitoring sensor that has been in service for a substantial time, fitted to the a train wheel bearing axle housing. Water streams, issuing from the StarStream device at 1 litre per minute, are used to treat the flat region of the sensor below the label, with and without ultrasound. There is never any detergent in the stream that leaves the nozzle, but part-way through the experiment some detergent is sprayed onto the surface to be cleaned, as described below.

Cleaning with water without detergent [figure 10(a)] produces no cleaning, as expected). Cleaning with UAS water without detergent [figure 10(b)] produces some cleaning, as indicated by the yellow arrow. Then some household detergent is sprayed onto the surface and subsequent cleaning by a UAS cold water stream (that stream containing no detergent) cleans the treated area [figure 10(c)].

Figure 11 shows cleaning of a small area on the metal mesh of an air intake cover that has been in service on a train. Such a convoluted surface would be particularly difficult to wipe or brush clean. Water alone does not clean it, and figure 11(a) shows that even when cold water is passed through the StarStream device, no visible cleaning occurs. Then household detergent is sprayed onto the mesh. After this, running cold water (without ultrasound) from the StarStream device onto the wire mesh does not produce cleaning [figure 11(b)], but when the ultrasound is activated, the UAS device is able to write a letter 'T' on the mesh by removing dirt from it, revealing shiny metal underneath.

Figure 10. Cleaning part of a sensor (the flat region below the label) after it has been in service on a train. (a) After cold water without ultrasound or detergent is passed through the StarStream device onto the surface. (b) After cold water without detergent but with ultrasound is passed onto the surface: the yellow arrow indicates some cleaning. (c) Some household detergent is sprayed on the surface and then it is treated with the UAS (there is no detergent in the stream that issues from the nozzle): the surface is cleaned. The video of this is available at: https://www.youtube.com/watch?v=qrW65G9j1LQ .

Figure 11. Cleaning part of the wire mesh of an air intake cover after it has been in service on a train. (a) Cold water without ultrasound and without detergent is passed through the StarStream device onto the surface, but produces no visible cleaning. (b) A cold water stream that is free of detergent, and has no ultrasound, is passed onto the surface after household detergent has been sprayed onto the surface. No visible cleaning occurs. (c) A cold water stream that is free of detergent, but has ultrasound in it, is passed onto the surface after household detergent has been sprayed onto the surface. Clear cleaning occurs. The video of this is available at: https://www.youtube.com/watch?v=HB2xLGpA2Tk .

IV. CONCLUSIONS

Although the power of the interaction between gas bubbles and liquids has been known about for over a century, that interaction nevertheless continues to provide new areas of research and innovation in ocean acoustics, industry and biomedicine, for both diagnosis/monitoring and therapy/processing.

Cold water cleaning is particularly important. Not only does it offer the prospect of reduced energy bills for the domestic, healthcare and industrial sectors, but in some circumstances (emergency vehicles, battlefield first aid, animal husbandry etc.) there is no opportunity to heat the water. Cleaning without additives is also important: it not only reduces the cost of purchasing additives, but reduces the additive load that is released into the environment, and offers opportunities for those substrates that cannot tolerate chemical burden within the cleaning water.

Hand cleaning is especially important. The Centre for Disease Control recommends that people wash their hands for 20 s in warm soapy water. The average for the UK is 6 s, often in cold water without soap. The authorities responsible for hand hygiene have tried for over a decade to change behavior for handwashing to achieve the 20 s goal in hot soapy water, but has not succeeded. The UAS technology offers an alternative, whereby instead of trying to change behaviour, the effort is placed in changing the water, so that those 6 s in cold water are as effective as 20 s in warm soapy water. We have not yet conducted the research that will allow comparison of the two scenarios, but that is a logical next step.

The glass tube study shown in figure 9 provides another intriguing scenario. In the distribution of beverages and foodstuffs, from their production and packaging to their delivery via pipework to vending machines or and drinks dispensers etc., it is very common for the inside of the tube to be coated with residual sugary liquid, which will promote the growth of bacterial biofilms etc. The use of bleaches and biocides to flush such tubing requires subsequent extensive flushing (to remove off-tastes and reduce ingestion hazard), often wasting significant volumes of product and leaving the tube, as when it started, with residual sugary deposit. The option of cleaning the tubes without additives, or with greatly reduced concentrations, is one that the UAS might offer.

As regards handwashing, the use of alcohol rubs for handwashing in hospitals provides a very useful technology, but the wider usage of water for washing hands, surfaces and tools in farms, abattoirs, kitchens, butchers and indeed across society, means that enhancing the effectiveness of cold water is important. On aircraft (and to a lesser extent cruise ships), food preparation areas are in close proximity to toilet and waste facilities, with a confined and concentrated set of strangers in circumstances of difficult hygiene. The UAS technology provides a particularly interesting route as it provides a mechanical challenge to microbes, which differs from the chemical challenges microbes usually face. In the broader context, as we approach possible catastrophes in healthcare and food production by 2050 as a result of the growth of AntiMicrobial Resistance (AMR), the strategy of increasing the variety of such challenges to microbe proliferation is an important strategy in combatting AMR, because the greater the range of challenges that we can deploy against microbes, the better placed we are to combat AMR.

Whilst all the preceding examples (figures 5-9) used no additives in the water, some household detergent had to be sprayed onto the surface for best cleaning with UAS in figures 10 and 11 (though the stream issuing from the nozzle was still detergent-free). The rail industry frequently uses pressure washers and additives, and so one might ask why test UAS here. One issue is that in some locations, the water ingress that might result from pressure washing could cause problems (in electrics, bearings etc.), and with the much lower water streams and reduced splashing seen in UAS< this is a far lower risk.

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